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A Study on the Air Flow and Odor Emission Rate from a Simplified Open Manure Storage Tank

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An Abstract. *This study presents a numerical evaluation of air flow and odor emission rate from an open manure storage tank. Odor emission rate is needed to facilitate the odor dispersion study and to compare different odor sources in terms of odor emission. The concentration at the manure surface, the tank dimensions, and wind speed were used to calculate air flow and the emission rate. The SIMPLER algorithm developed by Patankar (1980) and a two-layer turbulence model were used in the numerical simulation with a grid of 152 × 139. The predicted emission rate agreed with the field measurement results found in the literature. Experimental verification of the air flow showed that the flow pattern and velocity profile prediction were also in agreement with the experimental results. The calculated odor-emission rate was a function of the manure surface area, the odor concentration at the manure surface, the tank dimensions, and the wind speed.* **Keywords.** *Odor emission rate, Manure storage tank, Livestock, Numerical simulation.*

Odor is one of the major environmental concerns for the livestock industry. Complaints and lawsuits are filed because of odors generated from livestock facilities. Liquid manure storage is a major source of complaints and lawsuits. A number of studies were carried out to study odor dispersion and the area downwind that may be affected by a given odor source under given weather conditions. However, as shown by Li et al. (1994), dispersion studies are hindered due to lack of adequate methods to estimate the odor emission rate from a manure storage facility. The odor emission rate is the source term in the dispersion study. An accurate odor emission calculation is also needed to compare different storage facilities in terms of odor emission and to compare odor emission from the building with the manure storage.

Odor emission from a production facility can be estimated by knowing the exhaust-air flow rate and odor concentration in the exhaust air. For a manure storage facility, the problem is more complicated because the air exchange rate is difficult to obtain. Carney and Dodd (1989) calculated the emission rate from manure storage or treatment facility by multiplying the odor concentration at the source by the surface area of the source and by the prevailing wind speed. Bode (1991) studied odor and ammonia emission by covering tanks. Li et al. (1994) back-calculated the odor emission rate from field measurements of an odor plume width and odor intensity downwind by using the Gaussian plume model. Calculations were made for the emission rate through numerical simulation of the air flow in the tank head space.

The objective of this study was to calculate the odor emission rate from an open manure storage tank. The tank evaluated was an open, round tank as shown in figure 1. It has a diameter, D, and a height, H. The manure depth is h, and u_w is the wind speed.

Two major components control the odor emission rate from a manure storage facility: 1) the state of manure and the bio-process taking place that controls odor production. Without production, there is no emission, and 2) the state of the air above the manure surface, which controls the transport process. If the tank is sealed off, there is no emission. The two components affect each other. A complete modeling of the odor-emission process needs to consider the two components. Currently, however, the bio-processes in manure have been linked to some of the odor-contributing chemicals, but not to odor itself (Zhang, 1992). This study estimates the odor emission rate by focusing on the air above the manure. Given the wind speed and the tank dimensions, the air flow in the tank head space can be predicted. Given the concentration of odor at the manure surface (or the odor concentration of the

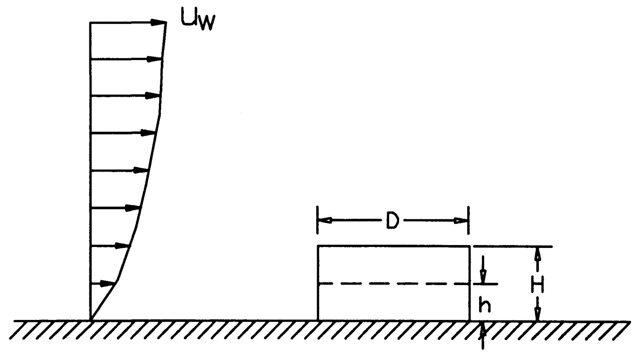

Figure 1–An open manure storage tank.

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air that is infinitely close to the manure surface), the emission rate can be predicted. The state of the manure is accounted for by the concentration at the manure surface. Different states of manure have different odor concentrations at the manure surface given the same air flow above the manure. By knowing the dimensions of the tank and wind speed, the emission rate can be estimated by measuring the odor concentration at the manure surface. This approach can be applied to anaerobic lagoons, earthen storage, and other similar sources. It also simplifies the practical use of the results.

Numerical simulation, similitude, experimental study by using a floating open bottom wind tunnel (Homans, 1988), and experimental study by using a box to cover the tank (Bode, 1991) were investigated. Numerical simulation with experimental verification was selected. The similitude study was not used because of the difficulty of measuring the emission rate in a scaled model. The other two experimental approaches were not used because of the differences between the flow studied and the flow inside an open tank.

Numerical Simulation

Simplifications and Assumptions

The flow in the open, round tank is three dimensional (3D). However, three-dimensional numerical simulation is currently not feasible because of the available computer capacity. To simplify the problem, the circular tank was divided into four rectangular sections, as shown in figure 2. The numbers in parenthesis are the percentages of area each rectangle has in relation to the area of half the tank. Each rectangle was then treated as a section of an infinitely long rectangle and was treated as two dimensional (2D). The Ws are the widths of the tank segments and are 0.6, 1.2, 1.6, and 2H for the four rectangles, respectively. Instead of solving one 3D problem, four 2D problems were solved. Figure 3 shows the 2D problem that was actually solved. W in figure 3 can be W1, W2, W3, or W4 depending on which section is studied. D and H are tank diameter and tank height, respectively. U_w is the wind speed at 10 m above ground. The calculation domain was chosen from 6H upstream of the tank center to 21H downstream of the tank center in a horizontal direction and from the ground to 11H high. This domain was chosen based on the results of Baskaran and Stathopoulos (1992) and Thangam and Speziale (1992). Baskaran and Stathopoulos (1992) studied the influence of calculation domain on building envelop. Thangam and Speziale (1992) studied the flow past a backward-facing step using different computational domain.

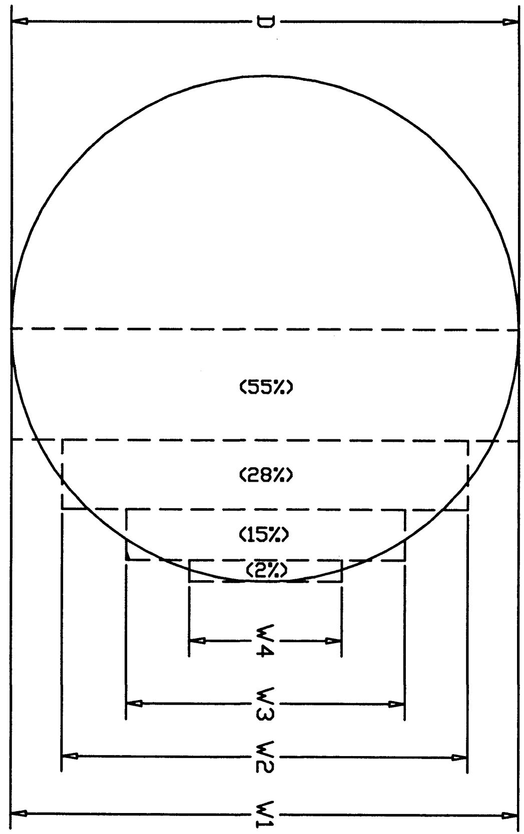

Figure 2–Dividing the tank into rectangles.

The following assumptions were made:

1. The process is at steady state.
2. The manure surface and the air are at the same constant temperature.
3. The odor concentration at the manure surface is the same over the entire surface.
4. All the odor ingredients are treated as one gas.
5. No other source or sink. No chemical reaction takes place in the domain of interest (fig. 3).

Turbulence Model Selection

The flow is turbulent with separation. The most widely used turbulence model is the standard two equation k-ε

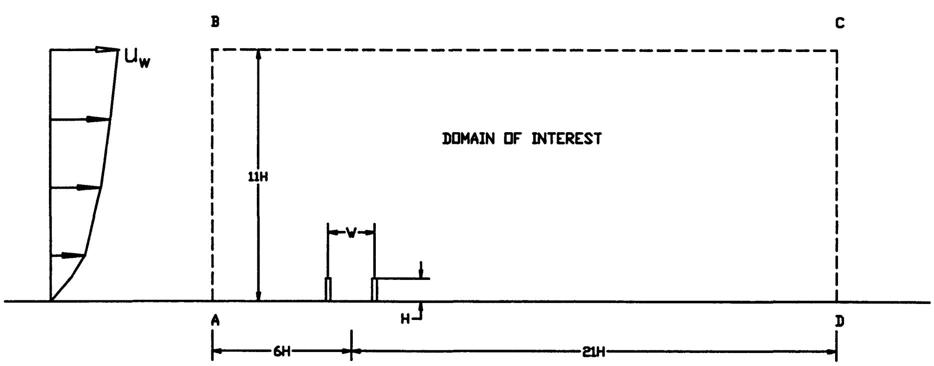

Figure 3–2D simplification of the tank.

model as proposed by Launder and Spalding (1974). The application of the k-ε model is limited to relatively simple flows (White, 1991). For flow with separation, the k-ε model is not adequate. To improve on the standard k-ε model, many different models were proposed. Liu (1994) did a literature review of turbulence models. One approach to improve the turbulence model is a two-layer approach. A one-equation turbulence model is used in the region close to the solid surface. The standard k-ε model is used elsewhere. The one equation model is generally comparable or better than the two-equation model (White, 1991) for complex flows (including separation). The standard k-ε model has proven its suitability for free shear flows. Combining these two takes advantage of both models and will avoid some of the weaknesses of a single model. The two-layer models proposed include Rodi et al. (1993), Chen et al. (1988), Goldberg (1992), and Mentor (1994).

A two-layer turbulence model proposed by Rodi et al. (1993) was used for this study. It uses a one-equation model based on $(v'^2)^{1/2}$ as velocity scale in the near solid surface region and the standard k-ε model elsewhere. The use of $(v'^2)^{1/2}$ as velocity scale was proposed by Durbin (1991). In the one-equation model, the following equations were proposed for the calculation of turbulent viscosity, μ_t, and turbulence dissipation, ε:

$$\mu_t = \rho \left(\overline{v'^2}\right)^{1/2} l_\mu \tag{1}$$

$$\varepsilon = \frac{\left(\overline{v'^2}\right)^{1/2} k}{l_\varepsilon} \tag{2}$$

where

$$l_\mu = c_{1,\mu} y$$

$$l_\varepsilon = \frac{1.3y}{1 + \dfrac{2.12v}{\left(\overline{v'^2}\right)^{1/2} y}}$$

$$c_{1,\mu} = 0.33$$

The calculation of $\left(\overline{v'^2}\right)^{1/2}$ is based on curve fitting through the DNS results. The fitted curve is:

$$\frac{\overline{(v'^2)}}{k} = 4.65 \times 10^{-5} y^{*2} + 4.00 \times 10^{-4} y^* \tag{3}$$

where

$$y^* = \frac{k^{1/2} y}{v}$$

Partial Differential Equations

The time-averaged equations of continuity, momentum, and conservation of species, and the equations from turbulence modeling can be put in one general form. The general form of the partial differential equations for the present flow-configurations can be written as:

Table 1. Summary of governing equations for the storage tank

Equation	ϕ	Γ_{eff}	S_ϕ
Continuity	1	0	0
Momentum	u_i	$\mu+\mu_t$	$-\partial p/\partial x+\partial/\partial x_j(\Gamma_{eff}\,\partial u_j/\partial x_i)$
Turbulent energy	k	$\mu+\mu_t/\sigma_k$	$\rho(G\dagger-\varepsilon)$
Dissipation‡	ε	$\mu+\mu_t/\sigma_\varepsilon$	$\rho(c_1\varepsilon^* G\dagger/k - c_2{}^*\varepsilon^2/k)$
Concentration	c	$\mu/Sc+\mu_t/\sigma_c$	0

† $G = \upsilon_t\,[(\partial u/\partial y+\partial v/\partial x)^2+2(\partial u/\partial x)^2+2(\partial v/\partial y)^2]$.
‡ For area that is not close to the solid surface only.

$$\mathrm{div}\left(\rho\vec{v}\phi\right) = \mathrm{div}\left(\Gamma_{eff}\,\mathrm{grad}\,\phi\right) + s_\phi \tag{4}$$

The generalized equation is in the form used in the SIMPLER scheme (Patankar, 1980), which was used in this study. The individual equations are summarized in table 1, and the constants used in the equations are listed in table 2.

Odor from a manure storage facility has many ingredients and many of them are not identified. The exact Schmidt number (σ_c and Sc) may never be known. The selection of Sc was based on Sc values of NH_3 and other ingredients (Reid, 1977). For most of the gases with Sc close to 1, σ_c is 1 (Treybal, 1980).

Boundary Conditions

The boundary conditions used are listed in table 3. The values in the table were nondimensionalized.

Detail of the Numerical Scheme

SIMPLER (Semi-Implicit-Pressure-Linked-Equations-Revised) algorithm (Patankar, 1980) was used to numerically solve the partial differential equations. It uses a control volume method and staggered grids to discretize the partial differential equations. The discretized equations are solved using TDMA (Tri-Diagonal-Matrix-Algorithm). A detailed discussion on SIMPLER can be found in Patankar (1980). DEC 3000 workstations from Digital Equipment Corporation were used for the simulations.

The convergence criteria used for this study were as follows.

Flow field:

$$r_c < 2.0 \times 10^{-6} \tag{5}$$

where r_c is the residual of continuity equation.

Conservation of species:

Table 2. The constants used in the equations

c_μ	c_1	c_2	σ_k	σ_ε	Sc	σ_c
0.09	1.44	1.92	1.0	1.3	1.0	1.0

Table 3. The boundary conditions used in numerical simulation

	u	v	k	ε	c
AB*	$(y/11)^{1/7}$	0	0.02	$0.1k^{3/2}$	0
CD*	$(y/11)^{1/7}$	0	$\partial k/\partial x=0$	$\partial\varepsilon/\partial x=0$	$\partial c/\partial x=0$
BC*	1	0	$\partial k/\partial y=0$	$\partial\varepsilon/\partial y=0$	$\partial c/\partial y=0$
Solid surface	0	0	0	†	$\partial c/\partial()$‡$=0$
Manure surface	0	0	0	†	1.0

* See figure 3.
† No boundary condition needed.
‡ May be $\partial c/\partial x$ or $\partial c/\partial y$ depending on the location.

$$\left(\frac{\left|c_{i,j}^{n+1} - c_{i,j}^{n}\right|}{c_{i,j}^{n}}\right)_{max} < 10^{-4} \qquad (6)$$

where

$c_{i,j}^{n}$ = odor concentration at grid point i,j at iteration number n

$c_{i,j}^{n+1}$ = odor concentration at grid point i,j at iteration n+1

A nonuniform grid of 152 × 139 (number of grid points in x direction and number of grid points in y direction) was used in the study. At least five grid-points were located in the near-manure surface region, for which the one-equation model was used. As pointed out by Thangam (1992), an appropriate grid resolution is critical to the success of a numerical simulation. Extensive grid sensitivity tests were run on the number and the location of the grid points. Less than 10% difference in emission rate was found by using a denser grid of 182 × 163 compared to a 152 × 139 grid.

Experimental Setup

To verify the numerical prediction, an experimental study was needed. Because of the size of the tank and the unsteady nature of the wind, an on-site experimental study was not possible. A wind-tunnel study on a scaled model was carried out to verify the numerical prediction. A wind-tunnel was constructed for this study (fig. 4). The width of the test section was 2.22 ± 0.013 m (87.5 ± 0.5 in.) and the height was 1.23 ± 0.005 m (48.3 ± 0.2 in.). The length of the test section was 2.90 m. Liu (1994) gave a more detailed description of the wind tunnel.

The 2D tank segments were simulated by two plexiglass plates. The scaled tank-height was 0.15 m (6 in.). The plates were placed on the side wall of the wind tunnel. The plate gave a wind-tunnel blockage of 6%. As shown by Hunt (1982), this blockage would lead to error in mean properties of less than 2%. The liquid surface was also represented by a plexiglass plate, which can be inserted into the notches in the tank plates. The different W/Hs were accomplished by using different surface plates. Different manure depths were simulated by placing the surface plates at different locations in the tank plates. The air velocity entering the wind tunnel test section was 1.39 m/s.

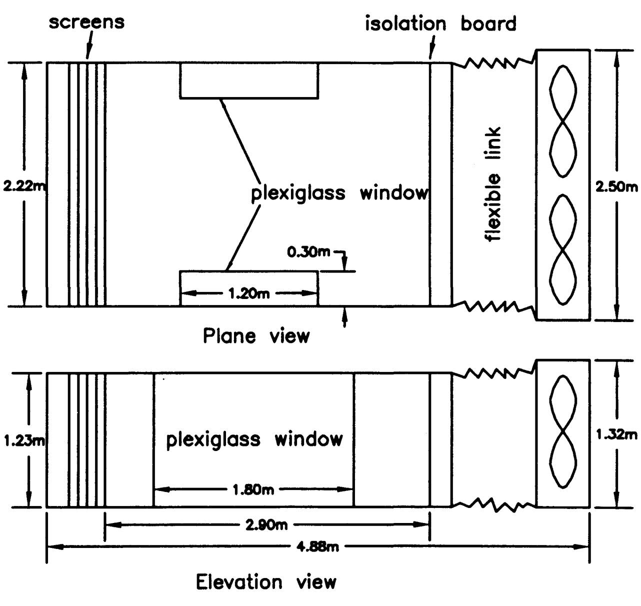

Figure 4–Wind tunnel setup.

Flow patterns in the wind tunnel were observed by using smoke generated by smoke candles (type 10-60, East Vermin Hill, Inc., Calif.). The flow pattern was photographed and also video taped. The observed flow pattern was used to verify the numerically predicted flow pattern.

To verify the predicted air velocity inside the tank, the air velocities inside the tank were measured. A hot-film velocity transducer of model 8470-50M-V from TSI, Inc., St. Paul, Minnesota, was used for the measurement. The transducer has a range of 0 to 5.00 m/s with an accuracy of ±3% of reading and ±1% full range. The velocity was measured for a 1 min duration at 0.5 Hz. The results were averaged to obtain the mean velocity for each point.

Results and Discussions

Comparison Between the Experimental and Numerical Results

A major part of this study is a numerical study of the air flow and odor emission rate from a manure storage tank. To verify the validity of the predicted results, wind-tunnel tests were made. However, the wind-tunnel test was not designed as a similitude study. Thus, separate numerical simulations were carried out according to the wind tunnel setup in addition to numerical simulation of the full scale, 2D tank segments. It was assumed that if the numerical simulation can predict the experimental study in the wind tunnel, it can also predict the flow in a full-scale tank.

The flow-pattern verification was done for W/H = 2 with a full, a half-full, and an empty tank. No noticeable difference in flow patterns was observed between the experimental results and numerical predictions for the half-full tank and the full tank. For the empty tank, the flow near the tank bottom in the experiment was almost still, and unsteady in contrast to the predicted low velocity but steady flow.

The magnitude of the air velocity in the empty tank and W/H = 2 along the center line of the simplified tank was shown in figure 5. This case was selected because the empty tank showed the most discrepancy between the experimental and predicted flow patterns in the tank bottom. Figure 5 shows that the air velocity prediction agreed well with the experimental result. The maximum velocity measured was 1.91 m/s, which agreed with the numerical prediction of 2.01 m/s.

Odor Emission Fluxes from the Tank

As shown in figure 2, the air flow in the open tank was simplified to four 2D segments. Three different manure depths were simulated: empty tank (the bottom covered with manure), half-full tank, and full tank. Thus, a total of 12 cases were simulated. The dimensionless odor flux (odor emitted per unit surface-area per second) for each case is listed in table 4. The emission flux for the tank was then calculated as the weighted (based on the segment area) average of the four tank segments. To convert the dimensionless flux to dimensional flux, multiply the

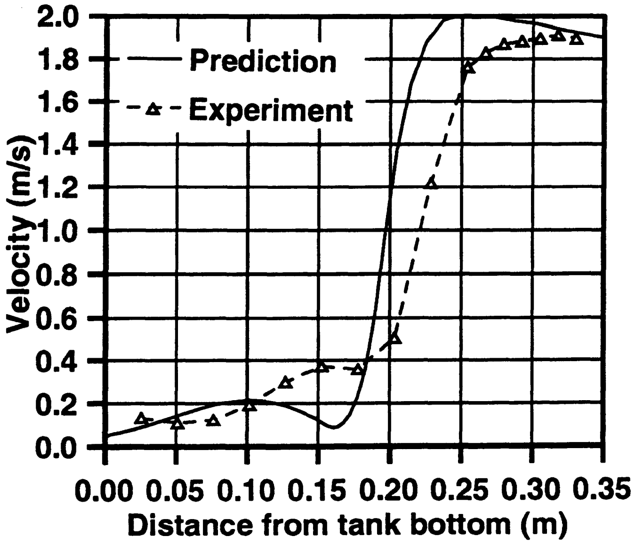

Figure 5–The velocity profile along the center of the tank (W/H = 2, h/H = 0).

dimensionless emission flux in table 4 by $u_w c_0 H^{1/7}$, where u_w is the wind speed at 10 m above ground (m/s). C_0 is the odor concentration at the manure surface (ou). H is the tank height (m). The dimensional odor flux has the unit of ou* m/s or ou* $m^3/(m^2s)$, where ou (odor unit) is the unit of odor concentration based on threshold measurement (Bundy et al., 1993).

The calculated results are in agreement with the existing experimental results found in the literature. Bode (1991) studied the odor and ammonia emission from tanks of 2 m × 1.9 m (diameter × height). A box with a fan providing air flow of 48 m^3/min was put on top of the tank. The exhaust air was measured for odor concentration. For pig manure, odor concentrations of 120-200 ou were measured in the exhaust. Odor concentration measurement was done using a dynamic olfactometer. Assuming an exhaust concentration of 160 ou, the odor emission rate from the tank was Q_{bode} = 128 ou* m^3/s. Assuming the air flow is equivalent to 4 m/s wind speed and the odor concentration on the manure surface was 5,000 ou, and the tank was half full, the odor emission rate would be Q =100 ou* m^3/s by using the result of this study. This is in agreement with the experimental result. The predicted results are also comparable to the results of Li et al (1994), who also used a dynamic olfactometer for odor concentration measurement (Bundy et al., 1993).

Application to Other Conditions

The tank simulated has a diameter to height ratio of 2 and Reynolds number of 2.7×10^6. To find out the sensitivity of the emission rate to tank dimensions and wind speed, Reynolds numbers of 1×10^6, 3×10^5, 1×10^5, 3×10^4, and 1.4×10^4 were simulated for W/H = 2 and h/H = 0.5 in addition to the Reynolds number of 2.7×10^6. Higher Reynolds number was not simulated because they would require a denser grid. The dimensionless emission fluxes calculated by using different Reynolds numbers are listed in table 5. The results showed higher nondimensional emission fluxes with the lower Reynolds number. But the change is relatively small for a large range of Reynolds numbers. The change was less than 80% when the Reynolds number changed from 2.7×10^6 to 1×10^5. Depending on the required accuracy, the results of this study can be used for a wide range of Reynolds numbers.

The conclusion that the nondimensional emission flux is higher at lower Reynolds number showed that the non-dimensional emission flux is greater at low velocities. However, the actual dimensional emission flux is actually less because the nondimensional emission flux is multiplied by $u_0 c_0$ to convert it to the dimensional emission flux. The conclusion of a higher emission rate at lower velocity (lead to lower Reynolds Number) should not be drawn.

Impact of Tank Segment Width to Height Ratio (W/H)

In the W/H range studied (0.6 to 2), the results in table 4 show a strong link between the emission rate and W/H for the 2D segments, except when the tank was full. Small W/H hindered the circulation movement of air in the tank, thus greatly reduced the emission rate. When the tank was full, an increase in W/H resulted in lower emission flux. The odor concentration of the air in contact with the manure surface was higher with the increase of W/H as air picks up the odor upstream. This reduces the concentration gradient and the emission rate. For tanks with diameter to height ratio other than 2, the result can only be used as a reference and further study is needed to determine the emission rate.

Impact of Manure Depth

Table 4 shows the odor fluxes calculated for each two-dimensional tank segment and for the tank at different manure depths. Generally, the emission rate was greater with the higher manure level for each 2D segment with the exception of W/H = 2, which showed the same emission rate for h/H = 0 and h/H = 0.5. The greater manure depth resulted in a higher velocity at the manure surface, which resulted in an increase in the odor emission rate. For W/H = 2, the manure depth of h/H = 0.5 resulted in a slightly higher velocity on part of the manure surface, but it also shifted the rotary zone to the leeward side of the tank, leaving part of the manure surface with low air velocity compared with the case of h/H = 0.

Uncertainties

The emission rate is directly related to diffusion coefficient D_{eff} ($D_{eff} = \nu/Sc + \nu_t/\sigma_c$). Two parameters control the diffusion coefficient: the Schmidt number (Sc),

Table 4. Calculated dimensionless odor fluxes (× 10^3)

	W/H=0.6	W/H=1.2	W/H=1.6	W/H=2	Tank
h/H = 0	0.18	0.78	1.2	1.3	1.2
h/H = 0.5	0.65	1.2	1.3	1.3	1.3
h/H = 1	2.4	2.3	2.3	2.3	2.3

† Multiply by $u_w c_0 H^{1/7}$ to get the dimensional flux in unit of ou*m/s.

Table 5. Dimensionless odor fluxes (× 10^3) at different Reynolds numbers

2.7×10^6	1×10^6	3×10^5	1×10^5	3×10^4	1.4×10^4
1.3	1.6	1.9	2.3	3.1	4.6

which controls the laminar portion of the coefficient, and σ_c, which controls the turbulent portion of the coefficient. The σ_c value is more dependent on the property of the flow and less dependent on the species in question, thus not a source of error. The Schmidt number is the property of the species and the media.

The Schmidt number used for this study of Sc = 1.0 was an estimate. The sensitivity of emission rate to Sc was checked by calculating the emission rate at Sc = 0.5 and 2.0. The results showed an Sc of 0.5 which gave an emission rate 50% higher than that of Sc = 1. An Sc of 2 gave an emission rate 35% lower than that of Sc = 1. If a better knowledge of the Sc number for odor in air is available, the odor emission flux can be estimated from the above results.

The 3D flow in the open manure storage tank was simplified to four 2D segments. This may underestimate the emission rate because 2D simplification forces more air to go over the tank which creates a larger recirculation zone. The 3D flow is more likely to reattach and flow into the tank. The exact amount of error due to 2D simplification is unknown at this point.

Using the Result in Practical Applications

The odor emission rate results can be used in practical applications. For example, it can be used to calculate the odor emission rate as the source term for dispersion modeling or comparing the strength of different odor sources. To use the results as listed in table 4, the tank dimensions, wind speed, and the odor concentration at the manure surface are needed. The odor concentration gradient near the manure surface is high. Sampling with a tube near the surface will probably underestimate the concentration on the surface significantly. The concentration is probably close to the saturation concentration on the surface and should be measured accordingly.

The wind speed should be measured at 10 m above the ground. Corrections should be made if the speed is not measured at that level.

Conclusions

This study evaluated the odor emission rate from a manure storage tank. The odor concentration at the manure surface, the tank dimensions, and wind speed were used to calculate the air flow and the odor emission rate. The numerical simulation used the SIMPLER algorithm and a two-layer turbulence model with a grid of 159 × 139. The predicted emission rate agreed with the results found in the literature. A wind tunnel was constructed for this study. Experiment verification showed that the flow pattern and velocity profile predictions were in agreement with the experimental results. The calculated odor flux was a function of many factors. It was found to be in the order of $10^{-3} c_0 u_w H^{1/7}$. The Reynolds number sensitivity test showed that the result can be used for a range of tank dimensions and wind speeds with acceptable error.

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